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Standard Guide for
Using Indoor Carbon Dioxide Concentrations to Evaluate Indoor Air Quality and Ventilation[1]

This standard is issued under the fixed designation D 6245; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

1. Scope

1.1 This guide describes how measured values of indoor carbon dioxide (CO_2) concentrations can be used in evaluations of indoor air quality and building ventilation.

1.2 This guide describes the determination of CO_2 generation rates from people as a function of body size and level of physical activity.

1.3 This guide describes the experimentally-determined relationship between CO_2 concentrations and the acceptability of a space in terms of human body odor.

1.4 This guide describes the following uses of indoor CO_2 concentrations to evaluate building ventilation–mass balance analysis to determine the percent outdoor air intake at an air handler, the tracer gas decay technique to estimate whole building air change rates, and the constant injection tracer gas technique at equilibrium to estimate whole building air change rates.

1.5 This guide discusses the use of continuous monitoring of indoor and outdoor CO_2 concentrations as a means of evaluating building ventilation and indoor air quality.

1.6 This guide discusses some concentration measurement issues, but it does not include or recommend a method for measuring CO_2 concentrations.

1.7 This guide does not address the use of indoor CO_2 to control outdoor air intake rates.

1.8 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.*

2. Referenced Documents

2.1 *ASTM Standards:*

D 1356 Terminology Relating to Sampling and Analysis of Atmospheres[2]

D 3249 Practice for General Ambient Air Analyzer Procedures[2]

E 741 Test Method for Determining Air Change in a Single Zone by Means of Tracer Gas Dilution[3]

2.2 *Other Documents*

ASHRAE Standard 62 Ventilation for Acceptable Indoor Air Quality[4]

3. Terminology

3.1 *Definitions*—For definitions and terms used in this guide, refer to Terminology D 1356.

3.2 *Definitions of Terms Specific to This Standard:*

3.2.1 *air change rate, n*—the total volume of air passing through a zone to and from the outdoors per unit time, divided by the volume of the zone (s^{-1}, h^{-1}).[5]

3.2.2 *bioeffluents, n*—gases emitted by people as a product of their metabolism that can result in unpleasant odors.

3.2.3 *single-zone, n*—an indoor space, or group of spaces, wherein the CO_2 concentration is uniform and that only exchanges air with the outdoors.

4. Summary of Guide

4.1 When investigating indoor air quality and building ventilation, a number of tools are available to understand the building being studied. One such tool is the measurement and interpretation of indoor and outdoor CO_2 concentrations. Using CO_2 concentrations to evaluate building indoor air quality and ventilation requires the proper use of the procedures involved, as well as consideration of several factors related to building and ventilation system configuration, occupancy patterns, non-occupant CO_2 sources, time and location of air sampling, and instrumentation for concentration measurement. This guide discusses ways in which CO_2 concentrations can be used to evaluate building indoor air quality and ventilation.

4.2 Section 6 discusses the rate at which people generate CO_2 and the factors that affect this rate.

4.3 Section 7 discusses the use of indoor concentrations of CO_2 as an indicator of the acceptability of a space in terms of perceptions of human body odor.

4.4 Section 8 describes the use of mass balance analysis to determine the percent outdoor air intake at an air handler based

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[1] This guide is under the jurisdiction of ASTM Committee D-22 on Sampling and Analysis of Atmospheres and is the direct responsibility of Subcommittee D22.05on Indoor Air.

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[2] *Annual Book of ASTM Standards*, Vol 11.03.

[3] *Annual Book of ASTM Standards*, Vol 04.11.

[4] Available from American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc., 1791 Tullie Circle, NE, Atlanta, GA 30329.

[5] A common way of expressing air change rate units is ach = air changes per hour.

on the measured CO_2 concentrations in the supply, return, and outdoor air intake airstreams.

4.5 Section 9 describes the use of the tracer gas decay technique to determine building air change rates using occupant-generated CO_2 as a tracer gas. The tracer gas decay technique is described in detail in Test Method E 741, and this section discusses the application of this test method to the special case of occupant-generated CO_2 after the occupants have left the building.

4.6 Section 10 describes the use of the constant injection tracer gas technique with occupant-generated CO_2 to estimate outdoor air ventilation rates. This technique is sometimes referred to as equilibrium analysis, and Section 10 discusses the use of this technique and the assumptions upon which it is based.

4.7 Section 11 discusses the use of continuous monitoring of CO_2 concentrations as a means of evaluating indoor air quality and ventilation in buildings. In this discussion, continuous refers to real-time concentration measurement recorded with a datalogging device over several days.

4.8 Section 12 discusses CO_2 concentration measurement issues, including measuring outdoor concentrations, sample locations for indoor concentration measurements, establishing the uncertainty of measured concentrations, and calibration.

5. Significance and Use

5.1 Indoor CO_2 concentrations have been described and used by some people as an indicator of indoor air quality. These uses have included both appropriate and inappropriate interpretations of indoor CO_2 concentrations. Appropriate uses include estimating expected levels of occupant comfort in terms of human body odor, studying occupancy patterns, investigating the levels of contaminants that are related to occupant activity, and screening for the sufficiency of ventilation rates relative to occupancy. Inappropriate uses include the application of simple relationships to determine outdoor air ventilation rates per person from indoor CO_2 concentrations without verifying the assumptions upon which these relationships are based, and the interpretation of indoor CO_2 concentrations as a comprehensive indicator of indoor air quality.

5.2 Outdoor air ventilation rates affect contaminant levels in buildings and building occupants' perception of the acceptability of the indoor environment. Minimum rates of outdoor air ventilation are specified in building codes and indoor air quality standards, for example, ASHRAE Standard 62. The compliance of outdoor air ventilation rates with relevant codes and standards are often assessed as part of indoor air quality investigations in buildings. The outdoor air ventilation rate of a building depends on the size and distribution of air leakage sites, pressure differences induced by wind and temperature, mechanical system operation, and occupant behavior. Given all of this information, ventilation rates are predictable; however, many of these parameters are difficult to determine in practice. Therefore, measurement is required to determine outdoor air change rates reliably.

5.3 The measurement of CO_2 concentrations has been promoted as a means of determining outdoor air ventilation rates per person. This approach, referred to in this guide as equilibrium analysis, is based on a steady-state, single-zone mass balance of CO_2 in the building and is sometimes presented with little or no discussion of its limitations and the assumptions on which it is based. As a result, in some cases, the technique has been misused and indoor CO_2 concentration measurements have been misinterpreted.

5.4 When the assumptions upon which equilibrium analysis is based are valid, the technique can yield reliable measurements of outdoor air ventilation rates. In addition, indoor CO_2 concentrations can be used to determine other aspects of building ventilation when used properly. By applying a mass balance at an air handler, the percent outdoor air intake in the supply airstream can be determined based on the CO_2 concentrations in the supply, return, and outdoor air. This percentage can be multiplied by the supply airflow rate of the air handler to yield the outdoor air intake rate of the air handler. In addition, the decay of indoor CO_2 concentrations can be monitored in a building after the occupants have left to determine the outdoor air change rate of the building.

5.5 Continuous monitoring of indoor and outdoor CO_2 concentrations can be used to study some aspects of ventilation system performance, the quality of outdoor air, and building occupancy patterns.

6. CO_2 Generation Rates

6.1 Human metabolism consumes oxygen and generates CO_2 at rates that depend on the level of physical activity, body size, and diet.

6.2 The rate of oxygen consumption V_{O_2} *in L/s of a person is given by Eq 1:*

$$V_{O_2} = \frac{0.00276\, A_D\, M}{(0.23\, RQ + 0.77)} \tag{1}$$

where:

A_D = DuBois surface area m^2,
M = metabolic rate per unit of surface area, met (1 met = 58.2 W/m^2), and
RQ = respiratory quotient.

The DuBois surface area[6] equals about 1.8 m^2 for an average-sized adult and ranges from about 0.8 to 1.4 m^2 for elementary school aged children. Additional information on body surface area is available in the EPA Exposure Factors Handbook **(2)**. The respiratory quotient, *RQ*, is the ratio of the volumetric rate at which CO_2 is produced to the rate at which oxygen is consumed. Therefore, the CO_2 generation rate of an individual is equal to V_{O_2} multiplied by *RQ*.

6.3 Chapter 8 of the ASHRAE Fundamentals Handbook, Thermal Comfort **(1)**, contains typical met levels for a variety of activities. Some of these values are reproduced in Table 1.

6.4 The value of the respiratory quotient *RQ* depends on diet, the level of physical activity and the physical condition of the person. It is equal to 0.83 for an average adult engaged in light or sedentary activities. *RQ* increases to a value of about 1 for heavy physical activity, about 5 met. Based on the expected variation in *RQ*, it has only a secondary effect on CO_2 generation rates.

6.5 Fig. 1 shows the dependence of oxygen consumption

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[6] The body surface area A_D in m^2 can be estimated from the formula $A_D = 0.203 H^{0.725} W^{0.425}$ where *H* is the body height in m and W is the body mass in kg **(1)**.

TABLE 1 Typical Met Levels for Various Activities

Activity	met
Seated, quiet	1.0
Reading and writing, seated	1.0
Typing	1.1
Filing, seated	1.2
Filing, standing	1.4
Walking, at 0.89 m/s	2.0
House cleaning	2.0-3.4
Exercise	3.0-4.0

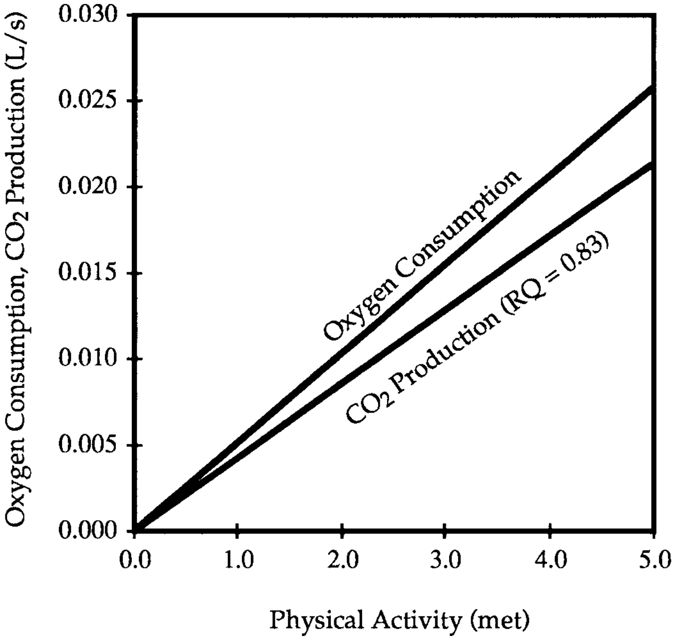


FIG. 1 CO_2 Generation and Oxygen Consumption as a Function of Physical Activity

and CO_2 generation rates on physical activity in units of mets for average adults with a surface area of 1.8 m^2. *RQ* is assumed to equal 0.83 in Fig. 1.

6.6 Based on Eq 1 and Fig. 1, the CO_2 generation rate corresponding to an average-sized adult (A_D = 1.8 m^2) engaged in office work (1.2 met) is about 0.0052 L/s. Based on Eq 1, the CO_2 generation rate for a child (A_D = 1 m^2) with a physical activity level of 1.2 met is equal to 0.0029 L/s .

6.7 Eq 1 can be used to estimate CO_2 generation rates based on information on body surface area that is available in the EPA Exposure Factors Handbook **(2)** and other sources. However, these data do not generally apply to the elderly and sick and, therefore, the user must exercise caution when dealing with buildings with such occupants.

7. CO_2 as an Indicator of Body Odor Acceptability

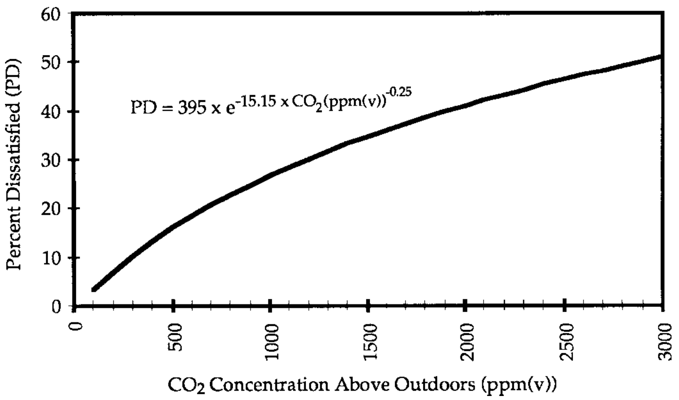
7.1 This section describes the use of CO_2 to evaluate indoor air quality in terms of human body odor acceptability and therefore, the adequacy of the ventilation rate to control body odor. The material in this section is based on a number of experimental studies in both chambers and real buildings and is the most well-established link between indoor CO_2 concentrations and indoor air quality.

7.2 At the same time people are generating CO_2 they are also producing odor-causing bioeffluents. Similar to CO_2 generation, the rate of bioeffluent generation depends on the level of physical activity. Bioeffluent generation also depends on personal hygiene such as the frequency of baths or showers. Because both CO_2 and bioeffluent generation rates depend on physical activity, the concentrations of CO_2 and the odor intensity from human bioeffluents in a space exhibit a similar dependence on the number of occupants and the outdoor air ventilation rate.

7.3 Experimental studies have been conducted in chambers and in occupied buildings in which people evaluated the acceptability of the air in terms of body odor **(3-7)**. These experiments studied the relationship between outdoor air ventilation rates and odor acceptability, and the results of these studies were considered in the development of most ventilation standards and guidelines (including ASHRAE Standard 62). This entire section is based on the results of these studies.

7.3.1 These studies concluded that about 7.5 L/s of outdoor air ventilation per person will control human body odor such that roughly 80 % of unadapted persons (visitors) will find the odor at an acceptable level. These studies also showed that the same level of body odor acceptability was found to occur at a CO_2 concentration that is about 650 ppm(v) above the outdoor concentration.

7.3.2 Fig. 2 shows the percent of unadapted persons (visitors) who are dissatisfied with the level of body odor in a space as a function of the CO_2 concentration above outdoors **(8)**. This figure accounts only for the perception of body odor and does not account for other environmental factors that may influence the dissatisfaction of visitors to the space, such as the concentrations of other pollutants and thermal parameters. Based on the relationship in Fig. 2, the difference between indoor and outdoor CO_2 concentrations can be used as an indicator of the acceptability of the air in a space in terms of body odor and, therefore, as an indicator of the adequacy of the ventilation rate to control the level of body odor. However, the relationship between percent dissatisfied and CO_2 concentration is also dependent on the personal hygiene of the occupants of a space, that is, their frequency of bathing, and the societal expectations of the visitors to the space. The individuals involved in the experiments on which Fig. 2 is based were office workers and university students with modern habits of personal hygiene



NOTE 1—This figure applies to spaces where human bioeffluents are the only sensory contaminants in the air.

FIG. 2 Percent of Visitors Dissatisfied as a Function of CO_2 Concentration (8)

from the United States, Denmark, and Japan. If the occupants of a space have different levels of personal hygiene and if the visitors have different expectations, than Fig. 2 would not necessarily apply.

7.3.3 The relationship between percent dissatisfied and CO_2 concentrations in Fig. 2 was seen experimentally **(3, 5, 7)** and the correlation was not strongly dependent on the level of physical activity. In addition, the relationship did not require that the indoor CO_2 concentration be at equilibrium.

7.3.4 The relationship described in Fig. 2 can also be derived based on the experimentally-determined relationship between percent dissatisfied and outdoor air ventilation rates in L/s. Based on a typical level of CO_2 generation per person and an assumption that the indoor CO_2 concentrations are at equilibrium, the outdoor air ventilation rates determined experimentally to result in a particular value of percent dissatisfied can be converted into indoor CO_2 concentrations to derive the relationship in Fig. 2.

7.3.5 The cited research has shown that if the difference between the indoor and outdoor CO_2 concentrations is less than about 650 ppm(v), then at least 80 % of unadapted persons (visitors) will find the level of body odor acceptable. This concentration difference corresponds to the indoor CO_2 concentration at equilibrium at a ventilation rate of 7.5 L/s per person. This ventilation rate also corresponds to 80 % acceptability based on experiment. The 650 ppm(v) concentration difference, combined with a typical outdoor CO_2 concentration of 350 ppm(v), is the basis of the commonly-referenced guideline value for CO_2 of 1000 ppm(v).

7.4 People adapt to bioeffluents over time, and adapted persons (occupants) will find a space acceptable at a higher level of body odor than unadapted persons (visitors). For adapted persons (occupants), the ventilation rate per person to provide the same acceptance is approximately one-third of the value for unadapated persons (visitors), and the corresponding CO_2 concentrations above outdoors are three times higher. While such a reduction in the ventilation rate may result in levels of body odor that are acceptable to adapted persons, the concentrations of other contaminants with indoor sources will increase which may result in poorer indoor air quality.

7.5 The use of CO_2 concentration differences as an indicator of body odor acceptability requires that the outdoor CO_2 concentration be measured. Paragraph 12.3 discusses these measurements.

7.6 This approach also requires the consideration of other sources of CO_2 10.5. The existence of other sources will increase CO_2 concentrations, and these elevated concentrations could be interpreted as a lower level of acceptability in terms of body odor. The existence of removal mechanisms will decrease CO_2 concentrations, and lead to the conclusion that the acceptability in terms of body odor is higher than its actual value. There is no practical way to adjust for the existence of significant sources or removal mechanisms, and therefore, CO_2 concentrations measured in these circumstances can not generally be used as a reliable indicator of body odor acceptability. Situations in which there might be significant indoor CO_2 sources are predominantly restricted to industrial processes. Significant indoor removal can occur when there are large numbers of plants in a building. However, no clear guidance exists on when CO_2 removal by plants is an issue.[7] Nonetheless, the user needs to be aware of the possibilities of indoor CO_2 source and removal mechanisms and avoid the misinterpretation of indoor CO_2 concentrations when these situations exist.

7.7 The use of CO_2 concentrations as an indicator of human body odor is distinct from any health effects associated with the CO_2 itself. Adverse health effects from elevated CO_2 have not been observed until the concentration reaches a value of 7000 ppm(v) to 20 000 ppm(v) **(8, 9)**, and these studies involved continuous exposure for at least 30 days. The threshold limit value (TLV) issued by the ACGIH for CO_2 is currently 5000 ppm(v) **(10)**.

7.8 While CO_2 concentrations can be an appropriate means of characterizing the acceptability of a space in terms of body odor, they do not provide information on the control of contaminants from other indoor pollutant sources such as building materials, furnishings, occupant activities, or from outdoor sources. On the other hand, indoor CO_2 concentrations may be useful to track other contaminants with source strengths related to occupancy. And while maintaining CO_2 concentrations within 650 ppm(v) above outdoors should maintain body odor at an acceptable level, the air quality may not be acceptable if there are other sources of sensory pollutants in the space. In addition, there may be other pollutant sources that are not sensory irritants but have adverse health effects on the occupants.

8. Percent Outdoor Air Intake

8.1 The percentage of outdoor air in the supply airstream of an air handler can be determined using CO_2 as a tracer gas based on mass balances of air and tracer at the air handler.

8.2 The percent outdoor air intake of an air handler % *OA* is equal to the volumetric airflow rate of outdoor air intake into the air handler Q_o divided by the airflow rate of supply air being delivered by the air handler Q_s. These airflow rates, and the recirculation airflow rate Q_r, are shown schematically in Fig. 3

8.3 Based on a mass balance of air and CO_2 at the air handler, the percent outdoor air intake is given by the following equation

$$\% OA = 100 \times (C_r - C_s)/(C_r - C_{out}) \tag{2}$$

where:

% *OA* = % outdoor air intake,

C_r = CO_2 concentration in the recirculation airstream of the air handler, ppm(v),

C_s = CO_2 concentration in the supply airstream of the air handler, ppm(v), and

C_{out} = CO_2 concentration in the outdoor air, ppm(v).

8.3.1 Eq 2 assumes that the indoor and outdoor air densities are equal. An alternative form of the equation can be derived that accounts for density differences between the indoor and outdoor air.

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[7] An indication of the importance of this removal mechanism may be obtained by measuring the indoor concentration after the building has been unoccupied for some period of time. If the concentration is well below the outdoor concentration, then removal may be significant.

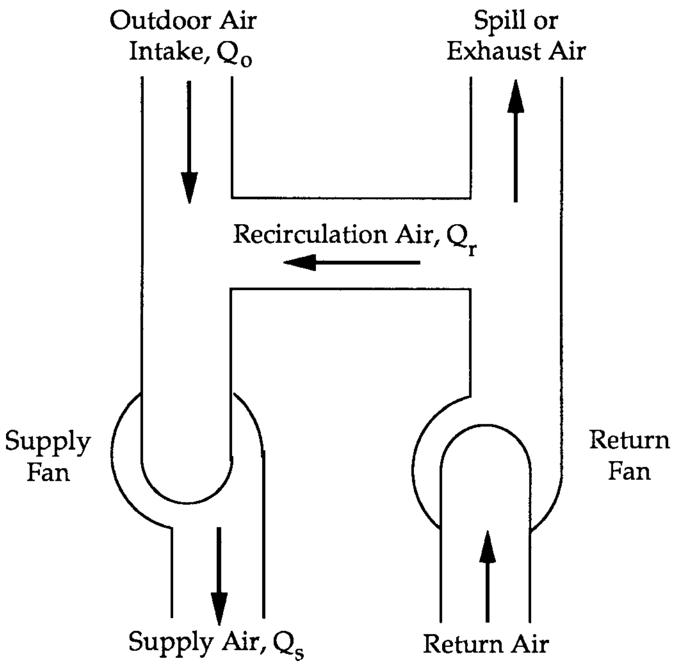

FIG. 3 Air Handling System Schematic

8.3.2 C_r can be measured in the return duct, which is often more accessible than the recirculation duct. C_r should be measured in a main return duct of the air handler, not a return vent in the occupied space or in a ceiling return air plenum.

8.3.3 C_s should be measured at the air handler, downstream to maximize mixing of the outdoor and return airstream. C_s should not be measured at a supply air outlet in the space.

8.3.4 Typical variations over time in indoor CO_2 concentrations are not a problem in the determination of % *OA*, however, C_s and C_r should be measured as close in time to each other as possible. Measuring these two concentrations within about 15 min of each other will generally be sufficient.

8.4 The precision of the percent outdoor air intake % *OA* determined with Eq 2 can be estimated using Eq 3.

$$\Delta\% = \%\,OA\,[(\Delta C_r^2 + \Delta C_{out}^2)/(C_r - C_{out})^2 + (\Delta C_r^2 + \Delta C_s^2)/(C_r - C_s)^2]^{0.5} \quad (3)$$

where:

$\Delta\%$ = precision of the percent outdoor air intake,
ΔC_r = precision of the measured CO_2 concentration in the recirculation air, ppm(v),
ΔC_s = precision of the measured CO_2 concentration in the supply air, ppm(v), and
ΔC_{out} = precision of the measured CO_2 concentration in the outdoor air, ppm(v).

8.4.1 Eq 3 only accounts for the precision of the measured concentrations and neglects any bias due to calibration and operator errors.

8.4.2 The magnitude of the difference between C_r and C_{out} relative to the precision of the measured CO_2 concentrations, is the main factor affecting the precision in % *OA*, with large values of this difference increasing the precision of % *OA*. This difference can be maximized by making the concentration measurements well into the occupied period of the day when the indoor CO_2 concentration has built up well above the outdoor concentration.

8.5 Using the value of % *OA* determined with Eq 2, the outdoor airflow rate being brought into the building by the air handler can be determined by multiplying % *OA* by the supply airflow rate. The supply airflow rate can be determined through an independent measurement procedure such as a pitot tube traverse of the supply airstream.

9. Tracer Gas Decay using Occupant-Generated CO_2

9.1 Whole building air change rates can be measured using the tracer gas decay technique in which occupant-generated CO_2 is used as a tracer gas and the measurement is conducted after the occupants leave the building.

9.2 Test Method E 741 contains a test method for tracer gas decay measurements of air change rates in a single zone. An air change rate measurement performed in accordance with Test Method E 741 determines the total rate at which outdoor air enters a single-zone space divided by the volume of that space. The outdoor air entry includes both infiltration through leaks and other openings in the building envelope and intentional outdoor air intake through mechanical ventilation systems. This test method applies to single-zone spaces, defined in Test Method E 741 as a space or set of spaces wherein the tracer gas concentration can be maintained at a uniform level and which exchanges air only with the outdoors.

9.2.1 The requirements of Test Method E 741 should be followed when performing a measurement using occupant-generated CO_2 as a tracer gas.

9.2.2 The requirements of Test Method E 741 cover apparatus, sampling duration and frequency, uniformity of tracer gas concentration in the space being tested, and calculation methods.

9.3 Using the tracer gas decay technique with occupant-generated CO_2 as the tracer gas involves some considerations not explicitly covered in Test Method E 741.

9.3.1 The decay technique is based on the assumption that there is no source of tracer gas in the building, which in the case of CO_2 means that the building is no longer occupied. In practice, an occupancy density of one person per 1000 m^2 or less will not impact the measurement results.

9.3.2 The tracer gas decay technique as described in Test Method E 741 assumes that the outdoor tracer gas concentration is zero, which is not the case with CO_2. However, if the outdoor concentration is constant during the decay measurement, then the tracer gas decay technique can be used by substituting the difference between the indoor and the outdoor concentration for the indoor concentration in the analysis contained in Test Method E 741.

9.3.3 Test Method E 741 requires that the concentration measurement precision be better than ±5 % of the concentrations during the decay. When using CO_2 as a tracer gas, this precision requirement must be applied to the difference between the indoor and outdoor CO_2 concentrations, that is, the precision of this difference must be better than ±5 % of its value throughout the decay.

9.3.4 In most buildings it takes some time for all of the occupants to leave the building, and during this time the indoor CO_2 concentration will decay. The indoor CO_2 concentration when the building is finally unoccupied depends on the concentration in the building when the occupants start leaving, the amount of time it takes for them to leave, and the outdoor air change rate of the building. Depending on the values of these parameters, the indoor CO_2 concentration may be too low once the building is unoccupied (based on the precision requirement in 9.3.3) to perform a reliable tracer gas decay measurement.

9.3.5 Test Method E 741 requires that the indoor tracer gas concentration at multiple points within the building differs by less than 10 % of the average concentration in the building. When using CO_2 this concentration uniformity requirement should be applied to the difference between the indoor and outdoor concentration. It may be difficult to meet this uniformity requirement in buildings with large spatial variations in occupancy or outdoor air delivery rates, or both.

9.4 CO_2 can also be released into an unoccupied building to perform a tracer gas decay test when occupant generation of CO_2 is insufficient to increase the indoor concentration. In this case, Test Method E 741 should be referred to for guidance on tracer gas injection.

10. Estimating Ventilation Rates using Equilibrium CO_2 Analysis

10.1 Under some circumstances indoor CO_2 concentrations can be used to estimate outdoor air ventilation rates based on the constant injection tracer gas technique. The application of the constant injection technique using occupant-generated CO_2 is sometimes referred to as equilibrium CO_2 analysis. Test Method E 741 contains a test method for constant injection tracer gas decay measurements of air change rates in a single zone. Equilibrium CO_2 analysis is a special case of the constant injection approach described in this guide.

10.2 *Constant Injection Technique and Equilibrium CO_2 Analysis*:

10.2.1 The constant injection technique, described in Test Method E 741, involves injecting tracer gas into a single-zone space at a constant and known rate. The gas is distributed in the zone such that it meets the concentration uniformity criteria from Test Method E 741. The tracer gas concentration in the zone is then measured in real-time. The average outdoor airflow rate into the zone during some time interval is calculated from the average concentration during that interval, the tracer gas injection rate, the zone volume, the length of the time interval, and the tracer gas concentrations measured at the beginning and end of the interval.

10.2.2 A constant injection tracer gas measurement performed in accordance with Test Method E 741 determines the total rate at which outdoor air enters a single-zone space. The outdoor air entry includes both infiltration through leaks and other openings in the building envelope and intentional outdoor air intake through mechanical ventilation systems. This test method applies to single-zone spaces, defined in Test Method E 741 as a space or set of spaces wherein the tracer gas concentration can be maintained at a uniform level and which exchanges air only with the outdoors.

10.2.3 The equilibrium CO_2 analysis approach is a special case of the constant injection technique described in Test Method E 741 in which the outdoor airflow rate is constant, the outdoor tracer gas concentration is nonzero and constant, the indoor CO_2 concentration is at equilibrium, there is a constant generation rate of CO_2 in the space, and there are no mechanisms of CO_2 loss, other than ventilation. In this approach, the outdoor airflow rate is given by Eq 4.

$$Q_o = 10^6 \times G/(C_{in,eq} - C_{out}) \tag{4}$$

where:

Q_o = outdoor airflow rate into the zone, L/s,
G = CO_2 generation rate in the zone, L/s,
$C_{in,eq}$ = equilibrium CO_2 concentration in the zone, ppm(v), and
C_{out} = outdoor CO_2 concentration, ppm(v).

10.2.4 Eq 4 can be written in terms of the outdoor airflow rate per person by substituting the CO_2 generation rate per person for *G*. In this case, the outdoor airflow rate per person is given by Eq 5.

$$Q_p = 10^6 \times G_p/(C_{in,eq} - C_{out}) \tag{5}$$

where:

Q_p = outdoor airflow rate per person into the zone, L/s per person, and
G_p = CO_2 generation rate in the zone per person, L/s per person.

10.3 *Requirements and Assumptions*:

10.3.1 The validity of Eq 4 and Eq 5 is based on several requirements and assumptions related to the single-zone tracer gas mass balance on which the equations are based.

10.3.2 Eq 4 and Eq 5 are based on the assumption that the zone to which the procedure is being applied acts as a single-zone with respect to CO_2 concentration, that is, the CO_2 concentration in that zone is uniform. Test Method E 741 specifies that the tracer gas concentration at representative locations throughout the zone differ by less than 10 % of the average concentration for the zone. The existence of concentration uniformity must be verified by measuring the indoor CO_2 concentration throughout the zone being tested. The measurement points must be well-distributed both horizontally and vertically in the zone being tested, including points in the individual rooms comprising the zone and multiple locations within the individual rooms. Based on these measurements, the uniformity criteria is evaluated based on the difference between the measured concentrations and the outdoor concentration.

10.3.3 Eq 4 and Eq 5 also require that the zone being tested is isolated from any other zones in the building in terms of airflow, unless those zones are at the same CO_2 concentration as the zone being tested. That is, there can be no airflow into the zone being tested from any other zones with a different CO_2 concentration (except the outdoors). In practice, this requirement means that these equations can not be applied to an individual room unless the concentration in the rest of the building, minus the outdoor concentration, is within 10 % of the average CO_2 concentration difference in the zone being tested. For rooms that do not meet this 10 % criteria, one must demonstrate that there is no significant airflow from such rooms to the test zone. This lack of airflow can be demonstrated visually by introducing smoke (with a smoke pencil or other such device) at the airflow paths between rooms.

10.3.4 The approach also requires that the CO_2 generation rate is constant and known. This requirement means that the number of occupants in the space and the rate at which they generate CO_2 are constant for a sufficiently long period of time while the concentration builds up to equilibrium. When using Eq 4, one needs to know the number of occupants and their average CO_2 generation rate. When using Eq 5, one only needs the average CO_2 generation rate. Determination of the average CO_2 generation rate requires consideration of the activity level and size of the occupants as discussed in 6.2.

10.3.5 The derivation of Eq 4 and Eq 5 requirement is based on a constant outdoor CO_2 concentration. This requirement is generally not a problem, but the outdoor concentration must be measured prior to and during the measurement of the indoor equilibrium concentration. It is not sufficient to assume that the outdoor concentration is at a typical value such as 350 ppm(v). Outdoor CO_2 concentrations can range from about 300 to 500 ppm(v) depending on time of day, season of the year, weather patterns, and building location.

10.3.6 Eq 4 and Eq 5 are based on the assumption that the outdoor air ventilation rate is constant. When using the equilibrium CO_2 analysis approach, one must understand and consider the factors affecting the ventilation rate of the space. These factors include outdoor weather conditions and the operation and control of any mechanical ventilation system. Typical variations in weather conditions will generally not result in significant changes in ventilation rate. However, if the building is mechanically ventilated, the control system may modulate the rate of outdoor air intake based on the weather. These control systems also vary intake rates based on time of day, interior air temperatures, and other factors. If the building is mechanically ventilated, the outdoor air intake controls must be understood, and the system operation status and the intake damper position must be inspected visually prior to and during the CO_2 concentration measurements to verify that they are not changing.

10.3.7 This approach also requires that the indoor CO_2 concentration is at equilibrium, meaning that the indoor CO_2 generation rate, the outdoor CO_2 concentration, and the outdoor airflow rate are constant for a sufficiently long period of time such that the indoor concentration stabilizes to a constant value. At this point, the rate at which CO_2 is generated in the space plus the rate at which CO_2 enters from the outdoors is equal to the rate at which CO_2 leaves the space by way of ventilation.

10.3.7.1 The time required to reach equilibrium depends only on the outdoor air ventilation rate of the space divided by the volume of that space, sometimes referred to as the outdoor air change rate in units of air changes per hour (ach). This relationship can also be described in terms of the time constant of the space, which is equal to the inverse of the outdoor air change rate.

10.3.7.2 The inverse of the outdoor air change rate is referred to as the time constant of the space. If the CO_2 generation rate (occupancy level), outdoor concentration and ventilation rate are all constant, and the indoor CO_2 concentration starts at the outdoor concentration, then it takes three time constants for the difference between the indoor and outdoor concentrations to reach 95 % of its equilibrium value. Fig. 4 is a plot of the calculated build-up of indoor CO_2 concentration for several different air change rates, assuming an outdoor concentration of 350 ppm(v) and an occupant density typical of office space.

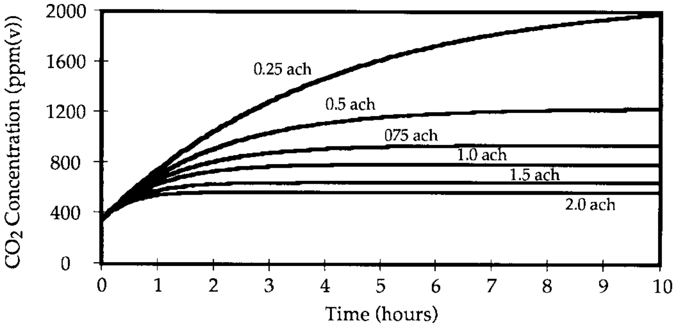

FIG. 4 Calculated CO_2 Build-Up

10.3.7.3 At an air change rate of 0.25 air changes per hour (ach), it takes 12 h of constant occupancy to reach 95 % of the equilibrium CO_2 concentration difference. This air change rate corresponds to about 3 L/s per person and an occupant density of seven people per 100 m^2 of floor area, and is not uncommon in office buildings under minimum outdoor air intake. At 0.75 ach (corresponding to about 10 L/s per person and more typical of office building ventilation rates), it takes 4 h for the indoor concentration to reach 95 % of equilibrium. At high air change rates, well above 1 ach, equilibrium is reached in 3 h or less.

10.3.7.4 In a classroom with 30 people per 100 m^2 of floor area and an outdoor air ventilation rate of 7.5 L/s per person, the air change rate is about 3.2 ach. Under these conditions it will take only about 1 h to reach 95 % of the equilibrium CO_2 concentration difference. If the outdoor air ventilation rate is 2.5 L/s then the air change rate will be 1.08 ach, and it will take about 2.8 h to reach 95 % of equilibrium.

10.3.7.5 In practice, the equilibrium requirement can be considered to be met when the change in the indoor-outdoor concentration difference over 1 h is less than the amount determined with Eq 6

$$\Delta C_{eq} = 180\ G/V \tag{6}$$

where:

ΔC_{eq} = change in indoor-outdoor concentration difference, ppm(v),
G = CO_2 generation rate in the zone, L/s, and
V = volume of the zone, L.

G is determined by multiplying the number of people in the zone by the average CO_2 generation rate per person, G_p. Both the values of G and V in Eq 6 need only be approximate.

10.3.7.6 In an office space with an average CO_2 generation rate of 0.0052 L/s per person, an occupant density of seven people per 100 m^2 and a ceiling height of 3 m, Eq 6 yields a rate of change in the indoor CO_2 concentration of less than 22 ppm(v) over 1 h to verify the existence of equilibrium. For a classroom with an average CO_2 generation rate of 0.0029 L/s per person, an occupant density of 30 people per 100 m^2 and a ceiling height of 2.5 m, Eq 6 yields a rate of change in the indoor CO_2 concentration of less than 63 ppm(v) over 1 h to verify the existence of equilibrium.

10.3.7.7 Continuous monitoring of indoor CO_2 concentrations can be useful for determining if equilibrium conditions exist, and evaluating the validity of Eq 6. However, one must still monitor building occupancy and ventilation system operation to ensure that these parameters are not changing.

10.4 When Eq 4 and Eq 5 are used to estimate outdoor air ventilation rates, the precision of these ventilation rates must be estimated. These estimates of the precision are based on the precision of the CO_2 generation rate and the precision of the CO_2 concentration measurements.

10.4.1 The precision of the outdoor airflow rate into the zone Q_o determined with Eq 4 can be estimated using Eq 7.

$$\Delta Q_o = Q_o\,[(\Delta G/G)^2 + (2\Delta C^2/(C_{in,eq} - C_{out})^2]^{0.5} \tag{7}$$

where:

ΔQ_o = precision of the outdoor airflow rate into the zone, L/s,

ΔG = precision of the CO_2 generation rate in the zone, L/s, and

ΔC = precision of the CO_2 concentration measurement, ppm(v).

10.4.2 The precision of the outdoor airflow rate per person Q_p determined with Eq 5 can be estimated using Eq 8.

$$\Delta Q_p = Q_p\,[(\Delta G_p/G_p)^2 + (2\Delta C^2/(C_{in,eq} - C_{out})^2]^{0.5} \tag{8}$$

where:

ΔQ_p = precision of the outdoor airflow rate per person, L/s per person,

ΔG_p = precision of the CO_2 generation rate per person, L/s per person, and

ΔC = precision of the CO_2 concentration measurement, ppm(v).

10.4.3 The precision of the measured CO_2 concentration ΔC can sometimes be obtained from the manufacturer's literature. If the precision is supplied by the instrument manufacturer, the user needs to understand the source and meaning of this value. Alternatively, one can determine the measurement precision based on calibrations using standard calibration gases. See Test Method D 3249 for a discussion of issues related to measurement accuracy of air analyzers.

10.4.4 The precision of the CO_2 generation rate per person ΔG_p depends on the uncertainty in the size and level of physical activity of the building occupants. Eq 1 can be used to estimate the precision of ΔG_p based on the uncertainties in A_D and M using standard calculation procedures for the propagation of error. For example, if A_D = 1.8 m^2 with an uncertainty of 0.1 m^2 and M = 1.2 met with an uncertainty of 0.1 met, then the CO_2 generation rate will equal 0.0052 L/s with an uncertainty of 0.005 L/s.

10.4.5 The precision in the CO_2 generation rate G for a group of people in the space is based on the uncertainties in the average CO_2 generation rate per person and the number of people.

10.5 This approach requires the consideration of sources of CO_2 in the space other than people as well as CO_2 removal mechanisms. Other sources include combustion processes in or near the space; CO_2 removal mechanisms include large numbers of plants. The existence of other sources will increase CO_2 concentrations, and these elevated concentrations could be interpreted as lower ventilation rates. The existence of removal mechanisms will decrease CO_2 concentrations, and the conclusion that the ventilation rate is higher than its actual value. There is no practical way to adjust for the existence of significant sources or removal mechanisms and, therefore, CO_2 concentrations measured in these circumstances can not generally be used to estimate ventilation rates reliably.

10.6 Even if the indoor CO_2 concentration has not yet reached equilibrium, Eq 4 and Eq 5 can be used to determine an upper bound on the ventilation rate. For example, if the difference between the indoor and outdoor CO_2 concentrations at equilibrium is 650 ppm(v) and the CO_2 generation rate in the space is 0.5 L/s, then Eq 4 yields a ventilation rate of 770 L/s. However, if the indoor concentration is not yet at equilibrium, then Eq 4 can still be used to determine that the ventilation rate is no higher than 770 L/s. This use of the Eq 4 and Eq 5 still requires that the ventilation rate and building occupancy is relatively constant. In other words, these equations can be used to confirm the inadequacy of ventilation but not necessarily its adequacy.

11. Continuous Monitoring of CO_2 Concentrations

11.1 Continuous monitoring of indoor and outdoor CO_2 concentrations using a datalogging device can be useful in investigations of building ventilation and indoor air quality. Such monitoring generally lasts one or more days and can be useful in the outdoor air, air handler return ducts, and within the occupied space.

11.2 Continuous monitoring of indoor CO_2 concentrations can be used to determine if equilibrium conditions exist, as discussed in 10.3. However, to verify the existence of equilibrium, one must monitor building occupancy and ventilation system operation to ensure that these parameters are also constant.

11.3 Continuous monitoring of indoor concentrations can be used to determine the actual peak CO_2 concentrations in a building or in a space within a building.

11.4 Continuous monitoring of indoor concentrations can also be used to determine building occupancy patterns, that is, when the occupants of a building, or a zone within a building, arrive and leave. If the building or zone ventilation rate is relatively constant, variations in indoor CO_2 concentrations can be used to indicate when the building or space is occupied.

11.5 Continuous monitoring of indoor and outdoor CO_2 concentrations can be used to monitor HVAC system operation in some situations. If the occupancy of a building or zone is relatively constant, variations in the CO_2 concentration can be used to indicate modulations in outdoor air ventilation rates due to economizer operation or modulation of VAV systems.

11.6 It is often helpful to supplement continuous monitoring of indoor and outdoor CO_2 concentrations with continuous monitoring of other variables such as indoor and outdoor temperatures and relative humidities.

11.7 In addition to, or in conjunction with, continuous monitoring, spot checks at multiple locations obtained with handheld instruments can be useful as an indicator of potential differences in ventilation rates among the monitored locations.

12. Measurement Issues

12.1 Due to the possibility of instrument drift over time and the impacts of travel on instrument performance, it is important to check instrument calibration before making CO_2 concentration measurements. This can involve both laboratory and field calibration checks. Manufacturer's instructions often cover the issue of calibration and should be followed. Field checks of calibration before, during, and after measurements can be useful for verifying proper instrument performance, and can include the use of both zero and span gases, but are not a substitute for a laboratory-grade calibration.

12.2 Many CO_2 concentration measurement instruments require a warm-up period for their operation to stabilize. The manufacturer's instructions should be consulted for the appropriate warm-up time and this guidance should be followed when using the device.

12.3 Some CO_2 concentration measurement instruments are affected by the temperature and relative humidity. The manufacturer's instructions should be consulted for the suggested operating conditions, and these factors should be taken into consideration.

12.4 *Outdoor CO_2 Concentration Measurement*:

12.4.1 When using CO_2 concentration for the purposes described in this guide, the outdoor CO_2 concentration must be measured.

12.4.2 Due to the existence of local variations in the outdoor CO_2 concentration and the possibility of exhaust air entrainment, the outdoor CO_2 concentration should be measured where the outdoor air is brought into the ventilation system serving the space. If the space is not mechanically ventilated, then the outdoor concentration should be measured as close as possible to those vents, windows, and other openings through which outdoor air would be expected to enter the space.

12.4.3 The outdoor concentration should be measured at several times before, during, and after the indoor CO_2 concentration measurements to determine a reliable value of the outdoor concentration and to verify its stability. Hourly measurements of the outdoor concentration will generally be sufficient. If the CO_2 concentration measuring instrument is sensitive to temperature, this effect must be taken into account when measuring the outdoor CO_2 concentration.

12.5 *Indoor CO_2 Concentration Measurement*:

12.5.1 The indoor CO_2 concentration sampling location should be selected to ensure a representative concentration value that is not unduly biased by the CO_2 sources (people) and low concentration ventilation air. The indoor sampling location should be selected by making measurements at multiple locations in the space and identifying one or more locations that yield a representative value.

12.5.2 The CO_2 concentration in an occupied space will generally not be uniform due to the high CO_2 concentration in the air exhaled by people (about 40 000 ppm(v)). Therefore, the indoor concentration should not be measured close to people. A distance of 2 m from any occupant is sometimes suggested as sufficient to avoid these effects.

12.5.3 The sampling location should be selected to avoid the low concentration air entering the space through open windows and supply air vents.

12.5.4 The indoor CO_2 concentration can be measured at a return or exhaust vent serving the space to obtain an approximate average concentration for the space. If there are multiple return or exhaust vents in the space, it may be necessary to sample at multiple vents to identify a vent that yields a representative value. Concern has been expressed regarding this approach due to the possibility of supply air short-circuiting to the return and resulting in a low CO_2 concentration in the return air relative to the occupied portion of the space. Measurements in return and exhaust ducts at some distance downstream of the vents can be subject to erroneous readings due to leakage into the ductwork.

13. Keywords

13.1 air change; air changes per hour; air change rate; building; carbon dioxide; indoor air quality; odor; tracer gas; ventilation

References

(**1**) *ASHRAE, Fundamentals Handbook*, American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., Atlanta, GA, 1997.

(**2**) *EPA, Exposure Factors Handbook*, U.S. Environmental Protection Agency, Office of Health and Environmental Assessment, EPA/600/8-89/043, 1989.

(**3**) Berg-Munch, B., Clausen, G., and Fanger, P.O. "Ventilation Requirements for the Control of Body Odor in Spaces Occupied by Women," *Environment International*, Vol. 12, 1986, pp. 195-199.

(**4**) Cain, W.S., Leaderer, B.P., Isseroff, R., Berglund, L.G., Huey, R.J., Lipsitt, E.D. and Perlman, D., "Ventilation Requirements in Buildings - I. Control of Occupancy Odor and Tobacco Smoke Odor," *Atmospheric Environment*, Vol .17, No. 6, 1983, pp. 1183-1197.

(**5**) Fanger, P.O. and Berg-Munch, B., "Ventilation Requirements for the Control of Body Odor," Proceedings of an Engineering Foundation Conference on Management of Atmospheres in Tightly Enclosed Spaces, American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., Atlanta, GA, 1983, pp. 45–60.

(**6**) Fanger, P.O., "Introduction of the Olf and the Decipol Units to Quantify Air Pollution Perceived by Humans Indoors and Outdoors," *Energy and Buildings*, Vol. 12, 1988, pp. 1-6.

(**7**) Rasmussen, C., Clausen, G.H., Berg-Munch, B. and Fanger, P.O., "The Influence of Human Activity on Ventilation Requirements for the Control of Body Odor," Proceedings of CLIMA 2000 World Congress on Heating, Ventilating and Air-Conditioning, Copenhagen, 1985, Vol 4, pp. 357-362.

(**8**) ECA (European Collaborative Action," Indoor Air Quality and its Impact on Man") *Guidelines for Ventilation Requirements in Buildings*, Report No. 11, EUR1449EN. Luxemborg Office for Official Publications of the European Communities, 1992.

(**9**) *EPA, Introduction to Indoor Air Quality.* A Reference Manual, U.S. Environmental Protection Agency, U.S. Public Health Service, National Environmental Health Association, EPA/400/3-91/003, 1991.

(**10**) *ACGIH, Threshold Limit Values for Chemical Substances and Physical Agents and Biological Exposure Indices,* American Conference of Governmental Industrial Hygienists, Cincinnati, 1995.

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